

Searching for I band variability in stars in the M/L spectral transition region

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ABSTRACT

We report on I band photometric observations of 21 stars with spectral types between M8 and L4 made using the Isaac Newton Telescope. The total amount of time for observations which had a cadence of <2.3 mins was 58.5 hrs, with additional data with lower cadence. We test for photometric variability using the Kruskal-Wallis H-test and find that 4 sources (2MASS J10224821+5825453, 2MASS J07464256+2000321, 2MASS J16262034+3925190 and 2MASS J12464678+4027150) were found to be significantly variable at least on one epoch. Three of these sources are reported as photometrically variable for the first time. If we include sources which were deemed marginally variable, the number of variable sources is 6 (29 percent). No flares were detected from any source. The percentage of sources which we found were variable is similar to previous studies. We summarise the mechanisms which have been put forward to explain the light curves of brown dwarfs.

Key words: Astronomical instrumentation, methods and techniques: techniques: photometric — stars: atmospheres – Brown dwarfs – stars: low-mass

1 INTRODUCTION

Ultra Cool Dwarfs (UCDs) are generally defined as having a spectral type later than M8. The temperature of stars on the boundary between M and L spectral classes is ~ 2200 K and the corresponding mass is $\sim 0.075 M_{\odot}$ (~ 80 Jupiter masses) (e.g. Basri et al 2000). This is the mass where a star cannot burn hydrogen in its core and are known as brown dwarfs. The 2MASS survey led to the detection of increasing numbers of these objects (e.g. Kirkpatrick et al 1999), with SDSS (e.g. Geballe et al. 2002), DENIS (e.g. Kendall et al. 2004) and WISE (e.g. Kirkpatrick et al. 2011) all leading to many additional discoveries. There are now nearly 2000 brown dwarfs which have a spectral type later than M9¹.

UCDs have provided a number of surprise's over the last few decades. A small number of UCDs show narrow-band pulsed radio emission which is 100% circularly polarised (e.g. Berger et al. 2001, Hallinan et al. 2008, Doyle et al. 2010). These pulses are thought to be produced by electron cyclotron maser emission and have an important diagnostic power to determine the stellar magnetic field strength and topology. The recent detection of a flare from a T6.5 dwarf (Route & Wolszczan 2012) implies a field strength of 1.7

kG which poses severe challenges for dynamo theories for magnetic field generation.

Observations of UCDs also allow the study of the atmospheric chemistry of very cool stars which has direct implications of our understanding of exo-planet atmospheres. At temperatures lower than ~ 2600 K, clouds begin to form and their depth and composition is expected to change with temperature (see for example Tsuji 2002, Allard, Homeier & Freytag 2012). However, there is still some controversy regarding the origin of periodic variations seen in some late type dwarf stars. Optical observations of TVLM 513-46546 (one of the radio pulsing systems which also shows X-ray emission) made over 7 years showed a stable rotation period of 1.96 hrs (Doyle et al. 2010, Wolszczan & Route 2014), which was taken to be evidence for a rotating magnetic spot. However, simultaneous g and r band data showed that their light curves were anti-correlated, which may point to long lived atmospheric dust clouds (Littlefair et al. 2008), although an auroral hot spot is an alternative explanation (Nichols et al. 2012).

Since the turn of this century there have been a number of photometric variability surveys of UCDs in both optical and IR bands (see, for instance, Radigan et al 2014, Wilson, Rajan & Patience 2014, Metchev et al. 2015). The optical surveys have largely been conducted in the I band and are most suitable to observe stars earlier than mid L spectral

¹ <http://www.johnstonsarchive.net/astro/browndwarflist.html>

types, whilst IR observations have focussed largely on later spectral types, since these stars become very faint in the *I* band. Given these surveys have a wide range of cadence and duration, definitive conclusions have been hard to make. However, it is now becoming apparent that in IR bands ~ 40 percent of sources with spectral types on the border between L and T types show strong variability on the timescale of rotation period, whilst ~ 60 percent of L/T sources outside this region show variability with an amplitude of ~ 1 percent (Radigan et al. 2014). In the *I* band, surveys show that many objects show low level variability but rather few show evidence of rotational signatures.

To increase the general body of knowledge of the photometric variability of sources in the M/L spectral transition region and search for sources which show a signature of a rotation period, we conducted a survey of 21 sources (some of which have not been studied before) using the 2.5 m Isaac Newton Telescope (INT) on the island of La Palma in 2014 and 2015 to search for variability on the several hour timescale. We present the results here and compare our findings with previous studies.

2 OBSERVATIONS

In selecting targets we used the SIMBAD database to obtain an initial broad target list of sources with spectral type in the range M8–L4. Since we had time on the INT at two different epochs we made a smaller target list for each epoch and then ensured that the observed sources were as distant as possible from the moon on the given date (the moon was close to full at each epoch). Some sources were chosen so that previous variability information was available for comparison and some sources had no previously published photometry. The details of the sources observed are shown in Table 1.

Observations were made using the INT with the Wide Field Camera and the Sloan Gunn *i* band filter between 2014 Oct 1–5 and 2015 Mar 31 – Apr 4. To reduce the readout time of the detector we only used a sub-array of Chip4, giving a typical readout time of 14 sec. The exposure time depended on the source brightness but was typically 2 min. (In Table 1 we note the *i* or *I* band mag of each source). For the first four targets we also obtained data using *grH α* filters which resulted in a cadence of ~ 8 mins (Given the sources are very faint in these observations and the cadence was poor they do not provide additional information). For the rest of the observations the cadence was 1.1–2.3 mins. The total amount of *i* band data was 4158 min (=69.3 hrs) – the amount of time where the cadence was < 2.3 min was 3508 min (=58.5 hrs).

The images were reduced using standard FIGARO (Shortridge et al 2004) routines. We obtained twilight sky flat fields and additional observations were made during the night of blank fields which allowed the removal of the effects of fringing. (On some nights thin drifting cloud was present which prevented the complete removal of fringing effects in each science image).

For each set of observations we performed aperture photometry of the target and two comparison stars in the field using the PHOTOM package (Eaton, Draper & Allen 2009)

which is part of the STARLINK² suite of software. Given the very red intrinsic colour of our targets, it was likely that these comparison stars would have different colours compared to the target. In some fields there were low numbers of potential comparison stars. However, for all observations we obtained photometry of the target and two comparison stars and derived three differential light curves: O–C1, O–C2 and C1–C2 (where O is the object and C1 and C2 is the first and second companion star). As an example we show the light curve for 2MASS J1022+5825 in Figure 1 made on two nights in April 2015, (this source was subsequently found to be variable at both epochs).

3 TESTING FOR VARIABILITY

One of the standard tests for variability in photometric light curves is based on evaluating the null hypothesis of ‘no variability’ by least squares fitting the light curve with a zeroth order polynomial (i.e. determine the best fitting constant level). One can then compute how well the constant model agrees with the data (e.g. the χ^2 test). Whilst this is a very simple and straight forward method, it suffers from severe problems such as flagging all light curves as variable if there are systematic errors and/or outliers (non-Gaussian data) involved. It is therefore beneficial to employ a method that is less sensitive to these effects.

We have chosen to employ the non-parametric Kruskal-Wallis H-test (Kruskal & Wallis 1952) to search for variability in our light curves. The H-test divides the light curve into *N* different samples (e.g. time windows) and after ranking the light curve values by flux, the test then measures the distribution of flux ranks in different samples. We defined time windows so that there were on average ten photometric points per window. This allows us to decide whether the population means in different samples are identical without assuming them to follow a Gaussian distribution. Furthermore, the errors of individual points are not used. These assumptions help to overcome some of the systematics, although clear systematic trends in the light curves will still produce false detections.

In order to minimize the number of false detections, we have employed two comparison stars for each target star (Finding charts for all targets can be accessed in the Supplementary material where comparison stars are indicated – see the end of this section for how to obtain this material). This way we can compute the H-test on differential magnitudes of O–C1, O–C2 and C1–C2. We can then compare the p-values of those three tests to filter out false variables. For instance, if both O–C1 and O–C2 tests give very low value for the null hypothesis of ‘no variability’, but also C1–C2 gives a very low value, any variability is most likely due to a systematic effect. However, on the other hand, if the C1–C2 p-value is much larger than the O–C1 and O–C2 ones, we are likely to have a real variable. We first identified those sources which had differential light curves O–C1 and O–C2 which were constant with a probability of $< 1 \times 10^{-3}$ (i.e. they were likely to be variable). Those sources then had to have a probability that the C1–C2 differential light

² <http://starlink.eao.hawaii.edu/starlink>

Table 1. The sources which we observed using the INT, where the source 2MASS identification is given in the first column. The *i* mag is taken from the SDSS and for others we infer the approximate *I* band mag (given in italics) from their 2MASS colours and spectral type (Liebert & Gizis 2006). We also indicate the spectral type where we have searched the dwarfarchives.org database and supplemented this with information from Liebert & Gizis (2006), Jenkins et al. (2009), West et al. (2011) and Zhang et al. (2010). The start of our INT observations is given in MJD, the duration of these observations and the number of photometric points. These are variable since in the earlier observations we alternated between a number of other filters. The INT Variability Column indicates whether the light curve is significantly variable (Y), not variable (N) or marginally variable (M).

Object	Mag (<i>i</i> / <i>I</i>)	Spectral Type	Observation Start (MJD)	Duration (mins)	No. Pts	INT Variability?
2MASS J02281101+2537380	18.2	L0	56931.957	160	21	N
2MASS J02511490-0352459	16.4	L1	56932.091	163	22	N
2MASS J02522628+0056223	17.1	M9	56932.970	187	25	N
			56934.102	205	188	N
2MASS J03202839-0446358	16.6	L0.5	56933.108	140	16	N
2MASS J19064801+4011089	18.2	L1	56933.832	154	139	N
			56935.938	130	120	N
2MASS J00154476+3516026	14.8	L2	56933.974	165	151	N
2MASS J19165762+0509021 (VB10)	12.6	M8	56934.841	164	151	N
2MASS J01353586+1205216	18.8	L1.5	56935.077	132	121	N
2MASS J03205965+1854233 (LP 412-31)	15.7	M8	56935.174	107	99	N
2MASS J18071593+5015316	16.2	L1	56935.836	130	120	N
2MASS J03395284+2457273	15.5	M8	56936.078	120	110	N
2MASS J03521086+0210479	16.4	L0	56936.172	120	110	N
2MASS J10224821+5825453	17.9	L1	57112.878	209	142	Y
			57115.984	230	121	Y
2MASS J13004255+1912354 (MN Com)	17.2	L3	57113.131	165	116	M
2MASS J07464256+2000321	16.1	L0+L1.5	57113.927	98	80	N
			57115.850	180	141	Y
2MASS J07472762+2608406	18.7	M9.5	57114.852	130	58	N
2MASS J11083081+6830169	16.4	L1	57114.946	270	121	M
2MASS J16262034+3925190	17.9	L4	57115.141	154	70	N
			57116.154	135	72	Y
2MASS J08175266+1947279	19.5	M9	57116.849	153	67	N
2MASS J12464678+4027150	19.8	L4	57116.975	166	75	Y
2MASS J13364062+3743230	18.7	L1	57117.113	191	84	N

curve was constant with a much higher probability. We then next visually inspected these light curves to determine if they showed any trends caused by differential colour extinction – none did. We indicate in Table 1 whether a source is classed as ‘variable’, ‘non-variable’, or ‘marginally’ variable. (The light curves and all cleaned CCD images can be accessed from information given in the Supplementary material which will be available on the MNRAS website and also <http://www.arm.ac.uk/~gar/intdwarf>).

4 RESULTS

Out of the 21 M/L stars which we observed using the INT, 4 (19 percent) show variability at one epoch. The Kruskal-Wallis H-test indicates they are constant with a probability of $< 2 \times 10^{-4}$. There are two additional sources which were also initially classed as variable but their C1-C2 differential light curve showed evidence for variability and were therefore classed as ‘marginally’ variable. If we include these marginal sources the number of variable sources in our sample becomes 6 sources (or 29 percent). Our small sample precludes us from determining whether sources of a given spectral type were more likely to be variable or not. The fraction of sources which we find to show photometric variability is very similar to that found by Koen (2013) in a

larger sample who found that 26 percent of M stars and 23 percent of L stars showing I_c band variability over the same timescale.

Of the four sources which were classed as variable, one (J1022) was variable at each of the two epochs (Figure 1) it was observed while J0746 and J1626 were found to be variable for only one of the two epochs they were observed (Table 1). (For those sources which were observed at two epochs, none showed significant differences in their mean flux). (We show the light curves for J0746+2000, J1626+3925 and J1246+4027 in Figure 2). None of these ‘variable’ light curves show evidence of periodic behaviour. The only source which shows short duration trends (J1246) is faint ($I \sim 19.8$) and would be a good candidate for further longer duration observations.

The origin of the variability of late M/early L type stars is still a matter of some debate, with starspots, holes (or ‘spots’) in the stellar atmosphere (of the sort seen in the Jovian planets) or inhomogeneous cloud layers all being proposed. As the star rotates these features can cause photometric variations. Disentangling the effects is difficult but identifying sources which do show variability provide opportunities to make more detailed investigation of the causes. The fact that we find only $\sim 1/4$ of our targets to be photometrically variable suggests that most stars on the M/L

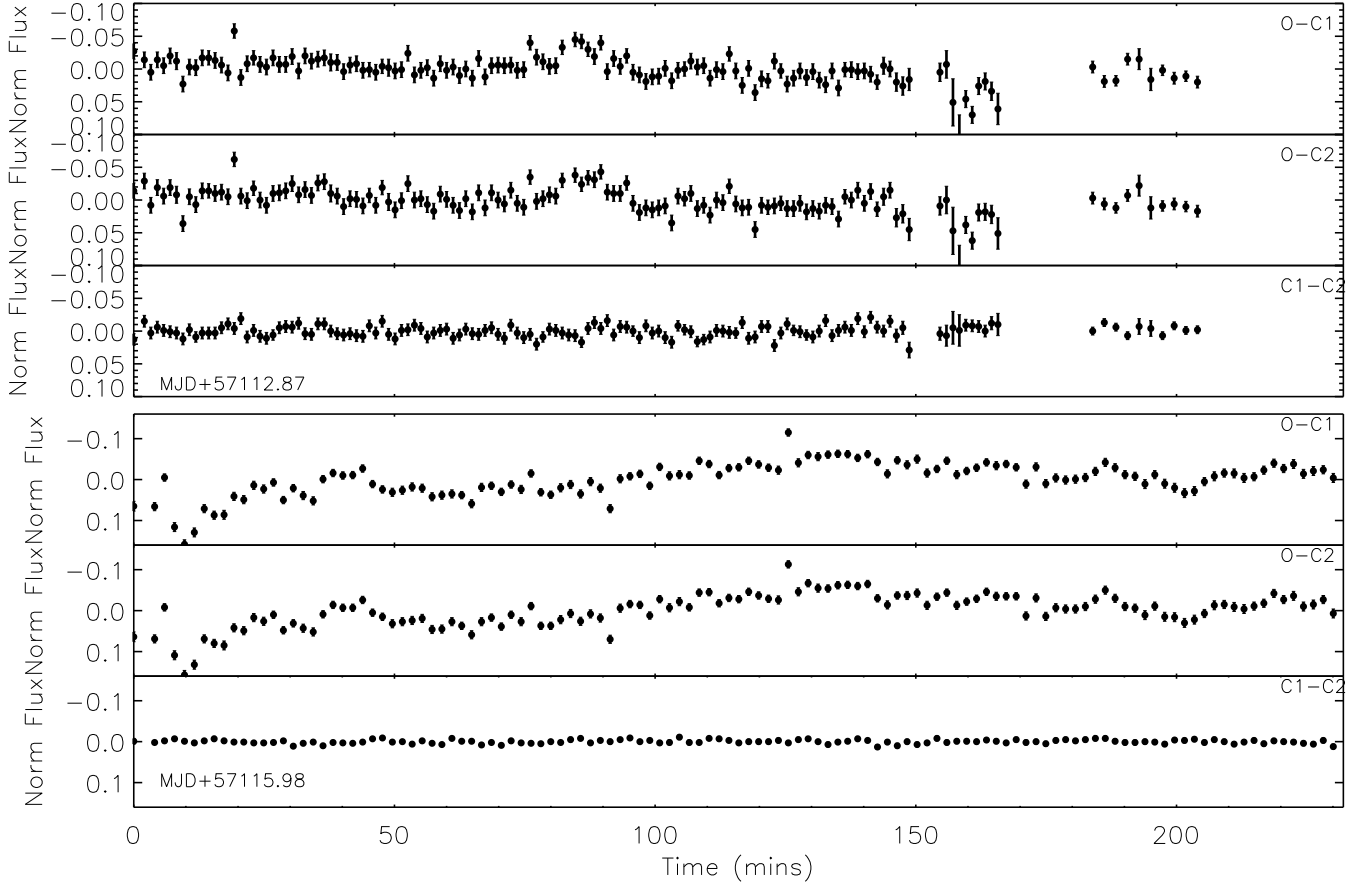


Figure 1. The light curve of 2MASS J1022+5825 made using the INT in the *I* band taken on two different nights in April 2015.

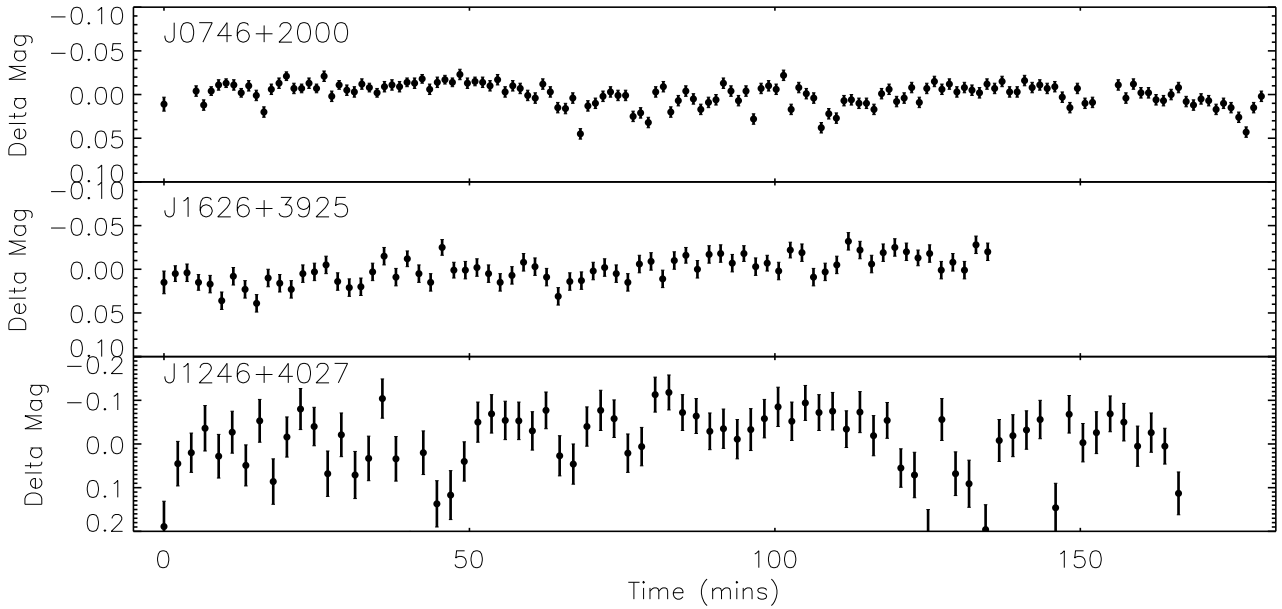


Figure 2. The light curve of the three sources, J0746+2000, J1626+3925, J1246+4027, which in addition to J1022+5825, were found to be photometrically variable.

boundary have fairly homogenous clouds. Stars which *do* show variability are more likely to have inhomogenous cloud layers or spots. In the Spitzer survey of 44 L3-T8 dwarfs, Metchev et al. (2015) conclude that the reason for the large number of irregular variables in their sample was due to rapid changes in the distribution of spots. This may also be the case here although at least some of our targets are known binaries. We now briefly comment on the sources in our survey which do show variability.

Although J1022 has shown variability in the profile of the H α emission line (Reiners & Basri 2008) it did not show long term *K* band variations in the study of Lopez Marti & Zapatero Osorio (2014). J1022 appears to be older than ~ 500 Myr and has a mass close to above the Lithium burning limit (Zapatero Osorio et al 2014). This appears to be the first detection of photometric variability on the several hour timescale.

J0746 shows strongly polarised radio emission on a period of 2.07 hrs (Berger et al 2009) and its optical light curve shows a period of 3.3 hrs (Harding et al 2013). Since J0746 is a known binary system (L0+L1.5) it is thought that J0746A is the source of the 3.3 hr modulation, while J0746B is the source of the radio pulses. Our first set of observations only covered 98 mins and no significant variability was detected but in the second set of observations we detect a significant modulation (based on the false alarm probability) on a period of 1.65 hrs – this is half the rotation period reported in Harding et al (2013). Given the observation duration was only 180 mins it is not surprising we do not identify the true rotational period. The other two variable sources, J1626 and J1246, do not appear to have been targeted for photometric variability before, and J1626 was found to be variable on one of the two epochs.

Kepler observations of the L1 dwarf WISEP J190648.47+401106.8 showed white light flares with energies in the range 6×10^{29} – 1.6×10^{32} erg and durations 3–160 min (Gizis et al 2013). We would have expected to easily detect a flare with an amplitude of 0.05 mag in our data. Assuming a luminosity of 1.4×10^{28} erg/s in the *Kepler* pass-band for an L1 star (Gizis et al 2013) and a flare lasting 10 min and a peak amplitude of 0.05 mag, this would imply a luminosity $\sim 3 \times 10^{29}$ erg. Gizis et al (2013) detected a flare with $E \sim 8 \times 10^{29}$ erg every ~ 100 hrs. Given our high cadence data covered a total duration of nearly 60 hrs the fact we did not detect any flares is not surprising.

5 CONCLUSIONS

Our survey of *I* band photometric variability in 21 stars with spectral types covering the M/L transition region show that 19 percent show clear variability over the several hour timescale. If we include sources which show marginal evidence of variability this number increases to 29 percent. This is very similar to the study of Koen (2013) who found 26 percent of M stars and 23 percent of L stars showing *I_c* band variability. Three of our variable sources have not been shown to be photometrically variable before. This makes them prime candidates for radio surveys searching for highly polarised radio emission in UCDs.

It is clear that observations covering a longer timescale

are essential to obtain more robust information on the variability of M and L dwarfs on different timescales and (perhaps most importantly) identify periodic behaviour. One such facility is the Next Generation Transit Survey (NGTS, Wheatley et al 2013) which is a wide field survey with a main goal of detecting sub-Neptune sized exo-planets, but given its red sensitivity it will be very well suited to long term monitoring of M/L dwarfs. Such facilities are not only better suited to searching for variability and will help inform models (e.g. Cooper et al. 2003, Helling et al. 2008, Stark, Helling, Diver 2015).

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